APPLICATION FOR UNITED STATES LETTERS PATENT

TITLE: DYNAMICALLY RECONFIGURABLE OPTICAL AMPLIFICATION ELEMENT

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DYNAMICALLY RECONFIGURABLE OPTICAL AMPLIFICATION ELEMENT

Field of the Invention

The present invention is directed to a dynamically reconfigurable optical amplification element and more particularly to such an element which can be implemented in a monolithic semiconductor structure.

Description of Related Art

In reconfigurable fiber-optic networks, the average amount of power on a single strand of fiber may change in time; for example, new wavelength channels may be used as more bandwidth is needed, or in optically switched networks, signals from different points of origin, and thus of different intensities, may occupy links at different times. The gain spectrum of an optical amplifier depends to some extent on the power of signals which it is amplifying. As a result, gain in reconfigurable networks may be expected to fluctuate undesirably and unintendedly in time. To avoid the occurrence of an unacceptable number of bit errors in information transmission, it is necessary for optical amplifying elements to account for, and respond to, such fluctuations.

Another task to which amplifiers are put in optical networks is wavelength conversion. One technique for wavelength conversion is disclosed in W. Idler et al, "10 Gb/s Wavelength Conversion with Integrated Multiquantum-Well-Based 3-Port Mach-Zehnder Interferometer," *IEEE Photonics Technology Letter,* Vol. 8, No. 9, September, 1996, pp. 1163-5. In a monolithic three-port Mach-Zehnder interferometer, a first port receives an unmodulated carrier wave $\lambda_c^{(cw)}$ having a wavelength λ_c. A second port receives a modulated signal wave $\lambda_s^{(data)}$ having a wavelength λ_s. The two waves interfere in the interferometer such that a third port outputs a modulated signal $\lambda_c^{(data)}$ having the wavelength λ_c. Both static and dynamic wavelength conversion are possible.

U.S. Patent Application No. ________ to *Thompson et al,* filed April 12, 2001, entitled "A method for locally modifying the effective bandgap energy in indium gallium arsenide phosphide (InGaAsP) quantum well structures," whose entire disclosure is hereby incorporated by reference into the present disclosure, teaches a method for locally modifying the effective bandgap energy of indium gallium arsenide phosphide (InGaAsP) quantum well structures. That method allows the integration of multiple optoelectronic devices within a single structure, each comprising a quantum well structure.

In one embodiment, as shown in Fig. 1A, an InGaAsP multiple quantum well structure 104 formed on a substrate 102 is overlaid by an InP (indium phosphide) defect layer 106 having point defects 108, which are donor-like phosphorus antisites or acceptor-like indium vacancies. Rapid thermal annealing (RTA) is carried out under a flowing nitrogen ambient, using a halogen lamp rapid thermal annealing system. During the rapid thermal annealing, the point defects 108 in the defect layer 106 diffuse into the active region of the quantum well structure 104 and modify its composite structure. The controlled inter-diffusion process causes a large increase in the bandgap energy of the quantum well active region, called a wavelength blue shift.

Another embodiment, as shown in Fig. 1B, uses two defect types, one to generate a wavelength blue shift and the other to decrease carrier lifetime. A first InP defect layer 110 contains slowly diffusing vacancy defects 114, while a second InP defect layer 112 includes rapidly diffusing group V interstitial defects 116. Rapid thermal annealing causes both types of defects to diffuse into the quantum well active region.

However, a satisfactory solution to the problem of the reconfigurable optical amplifier has not yet been found.

Summary of the Invention

It will be readily apparent from the above that a need exists in the art to take the above-noted fluctuation into account. It is therefore an object of the invention to provide a dynamically reconfigurable optical amplification element which can do so.

To achieve the above and other objects, a first embodiment of the present invention is directed to a dynamically reconfigurable amplification element which can re-equalize gain in response to changing needs on different channels or different fibers. Under the invention, the *Thompson et al* process, or any other suitable intermixing process, is used to provide a method of creating amplifying media with multiple sections, each providing optical gain centered about a different wavelength. This is difficult or impossible to do in the prior art. Each of these sections will be adjustable in its gain independently. As a result, it will be possible to reconfigure the combined amplifying spectrum according to time-varying network needs.

A second embodiment of the present invention is directed to an optical amplifier with the realization, on the same substrate, of passive (non-absorbing) waveguides, in order to form an interferometer for cross-phase modulation of one signal at one wavelength of a probe beam at a generally different wavelength. The resulting device serves as a wavelength converter over a broad spectrum.

Brief Description of the Drawings

Two preferred embodiments of the present invention will be set forth in detail with reference to the drawings, in which:

Figs. 1A and 1B show two embodiments of the technique of the above-cited *Thompson et al* patent application;

Fig. 2A shows a schematic diagram of a dynamically reconfigurable optical amplification element according to the first preferred embodiment;

Fig. 2B shows plots of the gain spectra of the three individual sections of the element of Fig. 2A;

Fig. 2C shows a plot of the total gain spectrum of the element of Fig. 2A;

Fig. 3 shows a flow chart of the operation of the element of Fig. 2A; and

Fig. 4 shows a schematic diagram of a wavelength converter according to the second preferred embodiment.

Detailed Description of the Preferred Embodiment

Two preferred embodiments of the present invention will be set forth in detail with reference to the drawings, in which like reference numerals refer to like elements or operational steps throughout.

As shown in Fig. 2A, an amplification element 200 includes a substrate 202 on which a quantum well structure 204 is formed. The quantum well structure is formed as three (or another suitable number) sections 204-1, 204-2, 204-3. each having a gain spectrum controllable by the application of a current I_1, I_2 or I_3 to an electrode 206-1, 206-2 or 206-3. The sections 204-1, 204-2, 204-3 are formed as separate quantum well active regions, but are formed in a single quantum well structure 204 to provide a monolithic structure.

Fig. 2B shows the manner in which each current I_1, I_2 or I_3 controls a corresponding gain spectrum G_1, G_2 or G_3. As shown, in each of the sections 204-1, 204-2, 204-3, the gain spectrum G_1, G_2 or G_3 is shifted both upward and in the direction of lower wavelength λ, so as to have a new maximum λ_1, λ_2 or λ_3. The sections have different gain spectra by virtue of their different compositions, their different thicknesses, a combination of the two, or any other suitable differing characteristics.

Fig. 2C shows the total gain G_{tot} as the sum of the gain spectra of Fig. 2B. Of course, since each of the three gain spectra G_1, G_2 or G_3 is separately controllable through separate control of the corresponding current I_1, I_2 or I_3, the currents could be selected to provide any of a wide variety of other gain spectra. Thus, a communication system including the amplification element 200 can be reconfigured on the fly to meet the changing needs of the network.

The sections 204-1, 204-2 and 204-3 can be made by any of the techniques disclosed in the above-cited *Thompson et al* patent application or by any other suitable intermixing techniques.

The amplification element 200 can be used in any suitable situation, such as the iterative process shown in the flow chart of Fig. 3. In step 302, the current gain spectrum of the element 200 is determined. In step 304, it is determined whether that current gain spectrum is suitable for the current incoming power spectrum. If so, then it is determined in step 306 that no action is required. Otherwise, the appropriate adjustments are made in step 308, through controlling the currents I_1, I_2, I_3 . In step 310, the process waits a predetermined time until the next time for which the gain spectrum of the element 200 must checked. After that predetermined time period, the process returns to step 302.

Another preferred embodiment, applicable to wavelength conversion, will be disclosed with reference to Fig. 4. The second preferred embodiment is based on the wavelength converter of *Idler et al,* with the use of a spatially selective intermixing process as taught in the above-cited *Thompson et al* patent application to create regions of broadband cross-phase modulation in one arm of the interferometer. Such spatially selective intermixing allows the wavelength converter and the regions of broadband cross-phase modulation to be formed as a monolithic structure.

The wavelength conversion element 400 is a Mach-Zehnder interferometer having left and right facets 402 and 404 and a main body 406. In the main body 406 is monolithically formed a series of waveguides including gates 408-1 through 408-6, of which gate 408-6 is introduced for symmetry reasons. The carrier wave $\lambda_c^{(cw)}$ injected through gate 408-1 is modulated in gate 408-3 by the counter-running $\lambda_s^{(data)}$ to produce $\lambda_c^{(data)}$. As taught in *Idler et al,* currents are provided to the gates to control the operation of the conversion element 400.

In the element 400 of the second preferred embodiment, as opposed to that of *Idler et al*, the gate 408-3 includes a region 410 of broadband cross-phase modulation which functions as an amplifier. The region 410 is formed by any of the techniques taught in the

above-cited *Thompson et al* patent application and can have a structure like that of one or more sections of the first preferred embodiment. The region 410 allows the element 400 to be dynamically reconfigurable, e.g., to handle different wavelengths as needed. Also, the process of Fig. 3 can be used with the element 400. Thus, if the carrier wave changes in wavelength over time or includes multiple wavelengths, the wavelength conversion element 400 can be adjusted dynamically to provide good results.

While two preferred embodiments of the present invention have been set forth above, those skilled in the art who have reviewed the present disclosure will readily appreciate that other embodiments can be realized within the scope of the present invention. For example, more or fewer regions can be provided as the number of wavelengths requires. Therefore, the present invention should be construed as limited only by the appended claims.